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TRIP REPORT
INTERNATIONAL CONGRESS ON APPLICATIONS OF LASERS AND ELECTRO-OPTICS
NOV 6-9, 1990, BOSTON, MASSACHUSETTS

L. Mannik

A paper describing a fundamental investigation of the CO_2 laser welding of steels at our Industrial Laser Laboratory was presented at the International Congress on Applications of Lasers and Electro-Optics (ICALEO). This meeting covered advances in a variety of applications of laser materials processing, with an emphasis on the use of YAG lasers. These included high speed drilling of aircraft hardware with the recently developed slab YAG laser, the welding of lamp leads and the welding of sleeves to repair steam generator tubes in nuclear power plants.

1.0 BACKGROUND

Ever since Research Division got involved with industrial lasers in 1987, I have been attending the annual laser materials processing conference at the International Congress on Applications of Lasers and Electro-Optics (ICALEO). Each year this meeting attracts approximately 100 researchers from around the world who are actively engaged in the development of applications of high power lasers for cutting, drilling, welding and surface treatment. A notable aspect of this year's conference was the large number of papers from North America: 31 of the 53 presentations, with the rest evenly divided between Europe and Japan. Among these were two from Canada, one from the Laser Institute in Alberta on laser-assisted arc welding and the other from our Industrial Laser Laboratory on the laser welding of steels. This investigation arose from our interactions with a local manufacturer of hose clamps, who was interested in assessing laser welding as an alternative to TIG. The manuscript for this paper, which will be published in the conference proceedings, is in the Appendix. I was gratified to have the opportunity to make this presentation because it served to make the materials processing community aware of Ontario Hydro and why we are interested in this area. In addition, I am hoping that the technical content

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of the paper will stimulate others to extend our study of the relationship between power, speed and penetration depth in laser welding to higher laser powers and material thicknesses. A number of the participants expressed an interest in this subject in the question period following the presentation and in subsequent informal discussions.

Following is a discussion of the highlights of the conference, which this year featured a large number of papers on YAG laser processing as an alternative to the CO_2 laser.

2.0 ADVANCES IN CO_2 LASER MATERIALS PROCESSING

2.1 Drilling

In conventional CO_2 laser drilling, plasma formation in the bottom of the hole limits the quality and speed of the processing by absorbing the 10.6 μm energy. (This is less of a problem at the 1.06 μm YAG laser wavelength.) Researchers at the Technical University of Denmark have developed a high-speed drilling technique capable of drilling up to 100 high-quality holes per second in metals as well as polymers. The method involves rotating the workpiece so that between successive pulses the plasma is expelled by the centrifugal forces. To date this drilling on the fly has produced 100 holes per second in 1 mm stainless steel, with the goal being 3 mm thickness. The resulting operating costs are much lower than for conventional laser drilling.

2.2 Cutting

Thick metal cutting has been investigated by Japanese researchers at Fanuc, a laser manufacturer. By using the TEM_{10} output mode to minimize distortion due to heating of transmissive optics and by optimizing the focus position to avoid constricting the assist gas flow, they have managed to cut 20 mm thick mild and stainless steel with good edge quality.

Dr. E. Beyer of the Fraunhofer Institute in Germany presented some results of a fundamental study of laser cutting which will eventually appear as part of a handbook to assist industrial users. Modelling combined with optical diagnostics (schlieren photography) of the supersonic gas flow within the kerf have been combined to improve the understanding of the cutting process. In practical terms this has led to the cutting of thick sections (15 mm stainless steel at ~1 m/min with a 5 kW laser and nitrogen assist gas) and to high speed cutting (100 m/min in 0.25 mm thick iron alloy with a 1300 W laser).

2.3 Welding

Most of the welding papers presented at the conference dealt with the YAG laser. The exceptions were my paper and a presentation by Dr. V. Merchant of the Laser Institute in Edmonton on the laser-assisted gas metal arc welding (LAGMAW). This is a method of reducing the amount of expensive laser energy required to produce welds in thick steel plate by combining it with inexpensive arc energy. In addition, preheating the material with an arc

increases the absorption of the material and hence reduces the laser energy required for welding. Bead on plate welding trials were performed to assess the effects of various parameters, such as the angle of the arc, electrode length and focusing position. For a given weld penetration, the use of the LAGMAW technique required 40% lower heat input than with arc or laser welding alone.

2.4 Surface Treatment

A paper from the University of Stuttgart described several methods of increasing the efficiency of laser hardening of metals. One of these concerned efforts to enhance the coupling of the laser energy to the workpiece by the use of graphite coatings, using a pyroelectric device to measure the surface temperature and keep it constant by controlling the laser power. Preheating the material produced an oxide layer which yielded even better performance. A second approach was to employ a flexible beam shaping unit which uses a fast modulated RF-excited CO_2 laser and scanning mirrors to form a desired intensity pattern on the workpiece. This group has also explored other lasers for surface hardening. Not surprisingly, they concluded that, because of the shorter wavelength, YAG and CO lasers offer the advantage of fiber optic beam delivery as well as better absorption.

2.5 Diagnostics

The paper with the most immediate benefit for the operation of our 1.5 kW CO_2 laser was a presentation on plastic burn analysis by David Whitehouse, who for many years has been a consultant for PRC. His approach was to determine if it is possible to obtain quantitative information from such burns, which have been used since high power lasers were developed to provide qualitative information on laser beam mode patterns and energy distributions. The conclusion of this research was that the uncontrolled variation in the usual burn patterns is due to fumes absorbing the laser beam and to light piping effects which deepen the burn pattern. By using a plastic block of PMMA (polymethylmethacrylate) to intercept half the beam and combining this with a nitrogen purge to remove fumes, it is possible to obtain burn patterns which reproduce the intensity variations in the laser beam to an accuracy of 10%. On a cost/benefit basis, this approach, costing a few dollars per measurement, could be far superior to the $10K laser beam analyzers commercially available.

3.0 ADVANCES IN YAG LASER MATERIALS PROCESSING

3.1 Fundamental Study

Dr. A. Matsunawa of the Welding Research Institute at Osaka University gave an interesting presentation on various aspects of YAG laser welding, considering three different modes of operation: continuous, pulsed and Q-switched (very short pulses). The main part of the talk focused on the interaction of the beam with the welding plume, which is generally a weakly ionized plasma. Losses due to this plume are predominantly due to Rayleigh scattering at short

wavelengths and due to inverse Bremsstrahlung (photon-induced electron acceleration) at longer wavelengths. It may be possible that at an intermediate wavelength the combination of these two factors yields a minimum in the net losses arising from the plasma.

3.2 GE Slab YAG Laser

In some ways, ICALEO '90 represented a coming out of the closet for GE and its slab laser. This alternative to the usual rod design, patented nearly 20 years ago, has for many years been promising outstanding performance in output power and beam quality to enable the YAG laser to better compete with the CO_2 laser in materials processing applications. Finally, it appears that the promise has been fulfilled. GE has produced an industrial workhorse used for internal applications which generates 500 W of average power in 50 J pulses with a peak power of up to 40 kW. Laboratory models have demonstrated outputs of >1 kW. The excellent beam quality (3X diffraction-limited) allows tight focusing of the slab YAG laser to achieve high energy densities for cutting, drilling and welding. Combined with fiber optic beam delivery, the laser has been used since 1986 at GE's Aircraft Engines facility to drill holes in steels up to 5 cm thick and in superalloys to depths of >2.5 cm. Compared to conventional YAG lasers,the slab has provided faster throughput as well as reduced recast and microcracking, mainly due to the higher vaporization rates generated by the higher power densities. In these drilling applications, the slab YAG laser has replaced electro-discharge machining (EDM) by providing four times the production rate. Researchers at GE's R&D Center have also been investigating drilling applications of the slab laser, targeted at the thousands of coolant holes typically found in aircraft hardware.

3.3 Other YAG Lasers

Following the expiration of GE's patent on the slab YAG laser design a few years ago, two companies made plans to come out with commercial devices based on this approach. One of these, Laser Technology Associates, has yet to produce its first product, although they claim to be building a 500 W laser similar to GE's. At the conference, this company presented a paper outlining research on diode pumping of slab YAG lasers. They are currently involved in a 5-year development program aimed at producing a 1 kW laser.

MLS Laser Systems is the only company with a commercially available slab YAG laser on the market. Their presentation reiterated the advantages of the slab design and included data on drilling, cutting and welding applications.

Lawrence Livermore National Laboratory has adapted some of their effort in building high power solid state lasers for inertial confinement fusion to the study of multi-kilowatt slab laser designs. With the use of a very high brightness lamp built by Vortek (a Canadian company), Livermore expects to be able to develop 6 kW of output, which would enable metal working capabilities previously unknown to industry.

Manufacturers of conventional rod YAG lasers are also making progress. A paper from Sandia

National Laboratories described a 1.8 kW YAG laser developed for the welding of aluminum alloys which is now being sold by Martek Lasers.

3.4 Nuclear Application

Along with Westinghouse in the US, a group at Mitsubishi Heavy Industries has pioneered the application of lasers to the repair of steam generator tubes in nuclear power plants. As reported in an earlier ICALEO trip report/1/, Westinghouse uses a CO_2 laser, while the Japanese have chosen the YAG laser because of its suitability for fiber optic delivery. They have developed a 15 mm diameter end effector rotated with an ultrasonic motor to enable welding of sleeves in the narrow space inside a heat exchanger tube. The welding is performed with 650 W of pulsed laser power and nitrogen assist gas to prevent spattering of the optics. More than 50,000 sleeves have been welded to date with very satisfactory results.

4.0 OTHER NOVEL PROCESSES

4.1 3D Machining

The Laboratory for Manufacturing and Productivity at MIT presented a concept for three-dimensional laser machining in which the primary disadvantage of current laser machining techniques, the low energy efficiency, is overcome by removing chunks of material. This is accomplished by using two intersecting laser beams to simulate conventional turning, milling and threading operations. The laser tool has been built but no experimental results are available yet. They also discussed the use of a water jet in tandem with a laser beam to reduce thermal damage, especially as applied to ceramics processing.

4.2 Architectural Materials

A Japanese group has investigated the use of lasers for processing cement-based materials and natural stone used in the construction industry. A CO_2 laser has been used to transform the surface of zeolitic mortar to produce a glassy, emerald green appearance. In addition to its decorative effect, the glass layer gives an improved surface hardness.

4.3 Welding of Lamp Leads

Since 1987 a General Electric plant in North Carolina has been fabricating electrical wires for halogen automobile headlamps using YAG lasers. Two conducting wires of different composition and size are joined by a laser welding system in which two optical fibers deliver the laser energy from opposite sides to produce a symmetrical weld. The wires are joined at the rate of 4 per second using a 250 W pulsed YAG laser. Replacement of the previous percussive welding with the laser has yielded a 20% increase in processing speed and a more uniform weld which has also produced productivity improvements in the lamp assembly.

4.4 Annealing of Steel Wires for Tires

One of the most commonly used applications of laser surface treatment is transformation hardening, in which a phase transformation of the surface layer results in a harder material. Nippon Steel in Japan has developed a method of laser annealing in which steel wire used in automotive tires is given increased fatigue strength without reducing the tensile strength by treating it with a 500 W CO_2 laser to give a softened outer layer. The conventional method of shot peening could only operate at slow speeds (<3 m/s), whereas the laser system, which makes use of a specially designed cone shaped mirror to concentrate the energy, has demonstrated speeds of 100 m/s. Up to 3 μm of the 300 μm diameter wire is annealed, resulting in a five times increase in fatigue strength.

5.0 INDUSTRIAL LASER LABORATORY CLIENT PROJECTS

One of the attractions of this conference is that it brings together most of the experts in laser materials processing from around the world, making it a golden opportunity to obtain free advice on some of the client-related projects we are dealing with in our Industrial Laser Laboratory.

In one of our recent projects, we were having some difficulty in cutting leather without producing darkened edges. Dr. E. Beyer of the Fraunhofer Institute had some useful suggestions, such as the importance of excluding oxygen by using high inert gas pressures and of making the laser spot as small as possible. Increasing the cutting speed also helps, which we had concluded from our own study. It was interesting to learn that laser cutting of leather is being successfully applied in England and Australia, as well as in Germany.

Dr. Beyer has also looked at the effect of preheating on the laser cutting of metals, of interest to the steel industry. Apparently his results are somewhat different from ours and we will be exchanging information on this topic in the near future.

I learned that a researcher at the University of Stuttgart has made progress in the laser hardening of low carbon steels by coating the material with graphite prior to laser treatment in order to increase the carbon content and thereby the ultimate hardness. This is of interest to the hardening of gear shift levers, which we were investigating two years ago for an Ontario car parts manufacturer.

6.0 SUMMARY

This year's laser materials processing conference at ICALEO featured a number of papers on YAG laser applications, including several performed with the recently developed GE slab design and one on the repair of steam generator tubes in nuclear power plants. A presentation from Ontario Hydro's Industrial Laser Laboratory on the laser welding of steels was well received and served to raise our profile in the laser materials processing community.

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REFERENCE

1. L. Mannik, Trip Report Seventh International Congress on Applications of Lasers and Electro-Optics, Ontario Hydro Research Division Report No 88-294-K.

APPENDIX

Laser Welding of Steels: Relationship between Laser Power, Penetration Depth,Welding Speed and Beam Polarization

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Abstract

Experimental data have been generated for the bead-on-plate keyhole welding of mild steel using the TEM_{∞} beam from a 1.5 kW CO_2 laser and a range of material thicknesses from 0.64 to 2.6 mm. For each thickness, the maximum welding speed was measured for laser powers from 600 to 1500 W, using the criterion of full penetration along a 5 cm length. Analysis of the data has yielded a simple correlation between laser power (P,kW), penetration depth (d,cm) and welding speed (v,cm/s). An analytical expression of this relationship has been derived for speeds from 1 to 16 cm/s. Stainless steel samples yield similar results. This correlation is interpreted in terms of the minimum energy envelope or range for laser welding as proposed by other workers and also in terms of the Swift-Hook and Gick theory of laser welding. Data on the effect of polarization are also presented and discussed in terms of the present correlation. Above a critical welding speed the welding efficiency is enhanced when the polarization of the laser beam is aligned with the direction of welding.

Introduction

The Research Division of Ontario Hydro has established a laboratory to investigate the industrial applications of high power lasers, with the objective of transferring this technology to local industries to improve their competitive position in the international marketplace. It was recognized that, to stay in business, Ontario manufacturers must keep pace with productivity gains achieved by competitors using emerging technologies such as laser materials processing. The role of the Industrial Laser Laboratory is to assess for our industrial clients the technical feasibility of applying lasers to specific manufacturing needs and to advise on the economic aspects of selecting a laser rather than some other tool. In the present situation of electrical demand threatening to outstrip supply, there is also a motivation to discover applications of high power lasers which consume less electrical energy than the processes they replace.

The laboratory houses a 1.5 kW CO_2 laser (PRC Model 1500) which produces a high quality output over a power range of 50 to 1500 W. The pulsing capabilities of this laser have proven useful in several applications. Motion of the workpiece under the focused laser beam is accomplished by means of an x-y positioning table together with a programmable motion controller. Speeds of up to 9 m/min are attainable with a travel of 30 cm in each direction.

During its three years of operation, the laboratory has addressed a variety of projects in laser drilling, cutting, welding and surface treatment for more than 20 industrial clients. One of these was a manufacturer of hose clamps interested in assessing laser versus TIG welding in its manufacturing process. In the course of assisting this client in optimizing the laser welding of 1 mm thick mild steel, we gathered data in our laboratory under a variety of conditions (laser power, welding speed, beam polarization and material thickness). Analysis of these results led to the development of the correlation presented here.

Background

There are several reports in the literature of attempts to collect data on the laser welding of steels and to generalize them in a form suitable for use as a practical guideline for industrial applications [1-3]. Most of these use as the key parameter the weld heat input or specific welding energy, defined as P/v, where P is the laser power at the workpiece and v is the welding speed. This parameter, which represents the energy deposited per unit length of weld, is usually correlated with weld penetration depth (d). In one such approach, researchers at Westinghouse used hundreds of experimental data points to derive a "minimum energy envelope" for mild steel and stainless steel [1,2]. This envelope is determined from the boundary of the experimental points on a plot of d against P/v and, as such, represents the deepest penetration achievable for a given specific welding energy.

In an extension of this approach, Merchant [3] has recently proposed that the specific welding energy per unit thickness ($Pv^{-1}d^{-1}$) be used to characterize the welds. When this parameter is plotted against penetration d, the result is a "minimum energy range" for the laser welding of steels, which indicates that the welding energy per unit thickness goes through a minimum at a thickness of ~4 mm. However, the data points on this plot are quite scattered, leading to uncertainties of close to 100% in the welding energy per unit thickness at the minimum value.

In our investigation of the laser welding of mild steel using various thicknesses of material, we have been able to correlate the data in a manner which simplifies the situation considerably. By plotting the welding energy per unit thickness against welding speed rather than penetration depth, we have discovered that all of our data fall on a single curve. Analysis of these results leads to a simple relationship between P, v and d which is valid for speeds above 1 cm/s and applies to stainless steel as well as mild steel. Furthermore, within this range of welding speeds, the derived correlation is consistent with the Swift-Hook and Gick theory of laser welding[4].

In an extension of this research, we also investigated the effect of the beam polarization on the welding process. This analysis confirmed the results of other workers by demonstrating that the most efficient laser welding of steels occurs when the direction of polarization is aligned with the weld seam.

Experimental Procedure

The laser used in this study was a PRC Model 1500 CO_2 laser, which produces up to 1.5 kW output in a TEM_{00} beam. Focusing this energy with a 127 mm focal length ZnSe lens yields a spot size ($1/e^2$) of 185 μm on the surface of the samples, corresponding to an M^2 beam quality parameter [8] of 1.5.

Bead-on-plate welding tests were performed on 5 cm wide samples of commercial grade mild steel with thicknesses ranging from 0.64 to 2.6 mm. There was no pre-treatment of the samples. The laser polarization was parallel to the weld seam, except for the polarization study described in the final section. A flow of argon cover gas was arranged coaxially with the laser beam (7.5 SLM) and also on the leading edge of the weld (23 SLM). For a given laser power and material thickness, the weld speed was determined by using the criterion of full penetration along the 5 cm seam length. Gas flow and laser focusing were kept constant during the tests.

Results and Discussion

The experimental data are summarized in Figure 1, in which the welding energy per unit thickness ($Pv^{-1}d^{-1}$) is plotted against the welding speed (v). It is evident that, when plotted in this form, the data lie on a single curve. In determining an analytical representation for this curve, it is useful to re-plot the data in terms of the laser power per unit thickness (P/d) against the welding speed (Figure 2). In this form, it is apparent that the data can be separated into three regimes, depending on the speed. At low speeds (below 1 cm/s), there is a sharp rise in power per unit thickness with increasing speed, but we have not quantified the dependence because of the difficulty of obtaining data at very low welding speeds. At intermediate speeds (1 cm/s≤v<10 cm/s), there is a linear increase of power per unit thickness with welding speed which is represented by $P/d = 3.83 + 0.69v$. At high speeds (v≥10 cm/s), the slope of the line increases and the data are consistent with a straight line through the origin represented by $P/d = 1.072v$. In these equations the parameters were determined by a least squares regression analysis. Also shown in Figure 2 are a few data points generated using samples of 301 and 304 stainless steel. These are consistent with the mild steel data, at least in the low and intermediate speed regimes.

Using this analysis, we can return to Figure 1 and draw a curve through the data points, represented by $Pv^{-1}d^{-1} = 0.69 + 3.83/v$ (1 cm/s≤v<10 cm/s) and $Pv^{-1}d^{-1} = 1.072$ (v≥10 cm/s). The form of the curve below 1 cm/s is uncertain because of the low number of data points in this region.

While we have not performed a comparable study with a TEM_{01*} beam, it is expected that this higher order mode would yield significantly higher values of P/d, primarily because the larger focused spot size reduces the power density, thereby resulting in a lower penetration depth for a given power level. This is confirmed by an analysis of welding data from the literature, most of which are generated with a higher order mode. As shown in Figure 3, these data tend to lie more than 10 % above the present results, ie for a given welding speed, at least 10% more power is required to achieve a certain penetration. The exception is Powell's data on the welding of stainless steel [5] which agree well with our results, possibly because the measurements were made with a low order mode laser beam. Obviously, other factors such as focusing optics, cover gas and the location of the focal point come into play as well; a detailed study of these factors would be worthwhile.

The correlation derived in this investigation implies that a given thickness of steel can be welded with the most efficient use of laser energy when a TEM_{00} beam is used and the speed of the keyhole welding is greater than 10 cm/s, so that the relationship $P/d = 1.072v$ applies. Under these conditions the fraction of the laser energy going into welding rather than material heating or other losses is maximized. This is related to the "weld energy boundary" or the "minimum energy envelope" of the Westinghouse compilation [1,2] referred to in the introduction, which represents the deepest penetration (d_{max}) achievable for a given specific welding energy (P/v). In terms of the present correlation, $P/d_{max} = 1.072v$, so that $d_{max} = 0.93\ P/v$. This agrees well with the data gathered by Westinghouse which gives, for thicknesses less than 3 mm, $d_{max} = P/v$ for both mild and stainless steels.

Using the present analysis, it is also clear why Merchant's plots of $Pv^{-1}d^{-1}$ against d gave a range of minimum energies [3]. Our correlation predicts that, at least for thicknesses up to ~3 mm covered by the experimental data, the parameter $Pv^{-1}d^{-1}$ will have a value which is determined by the welding speed rather than the penetration depth. In other words, data obtained at a constant welding speed should have a $Pv^{-1}d^{-1}$ value that is independent of d up to 3 mm. However, the data collected by Merchant represented a range of welding speeds and hence yielded a range of $Pv^{-1}d^{-1}$ values for a given value of d. In this regard, it would be interesting to explore the welding of thicker materials with a higher power TEM_{00} laser beam to determine the range of validity of this correlation.

It is instructive to consider the present correlation in the context of the well-known Swift-Hook and Gick (SHG) theory of laser welding [4]. Nearly all the data presented here (v>1 cm/s) correspond to the high speed limit in the SHG formulation, in which case the theory predicts a linear relationship between the normalized power input X and the normalized melting width per unit depth Y of the form

$$Y = 0.483\ X. \qquad (1)$$

The dimensionless power input parameter is defined as $X = P/(dS)$, where P is the laser power (kW), d is the penetration depth (cm) and S is a heat function (kW/cm) obtained by integrating the thermal conductivity over the temperature rise. For steels, the heat function has a value of

0.36 kW/cm [4]. The other dimensionless parameter is defined by Y = vb/D, where v is the welding speed (cm/s), b is the melt width (cm) and D is the diffusivity, which for steels has the value 0.05 cm^2/s [4]. Substituting these values in Eq. (1) leads to

$$P/d = 14.9\ bv. \qquad (2)$$

Measurements of the melt width for each of the bead-on-plate welded samples were performed using an optical microscope. The data are shown in Figure 4 as a plot of melt width against welding speed. This result can be compared to the predictions of the SHG theory. The latter gives, using Eq. (2), $b = (Pd^{-1}v^{-1})/14.9$. Substituting the experimentally derived variation of $Pd^{-1}v^{-1}$ with v (Figure 1) leads to a dependence of melt width on welding speed as predicted by the SHG theory. This is also shown in Figure 4. It is evident that the two curves have a similar form. In fact, if the constant in Eq. (2) were 21.0 rather than 14.9, the calculated melt widths would agree with the experimental values. In terms of the energy transfer efficiency, defined by SHG as that proportion of the beam energy which is actually transferred to the material, this implies that our measurements correspond to an average efficiency of 14.9/21.0 or 71%. A recent publication [9] described measurements of the energy transfer efficiency as a function of welding speed which yielded, for argon cover gas, values ranging from 28 to 64% for speeds up to 14 cm/s. In that investigation, the role of multiple reflections inside the keyhole in explaining these results was emphasized. The research of Beyer et al. [7] has demonstrated the importance of aligning the direction of polarization with the weld seam in order to maximize the energy absorbed in each reflection. Our own study of the effect of beam polarization on the laser welding of mild steel confirms these findings.

Measurements of the laser welding of mild steel with the polarization perpendicular to the weld seam are summarized in Figure 5, which also includes the data for parallel polarization as represented by the linear fit. Below 4 cm/s the results are independent of the direction of polarization. At higher speeds, welding with the polarization perpendicular to the weld seam requires a significant increase in the laser power to achieve a particular penetration depth. In other words, the energy transfer efficiency is much lower with the perpendicular polarization. Using a least squares regression analysis, we determine that, above 4 cm/s, the linear increase of power per unit thickness with welding speed is represented by P/d = 1.74v. The critical welding speed, which represents the threshold above which polarization effects are observed, is determined by the intersection of the parallel and perpendicular data to be 3.7 cm/s. Beyer and his co-workers have performed extensive research on this subject and have found that the critical speed depends on many factors, including the laser power [7]. At 1.5 kW they observed a value of 4.8 cm/s. Based on the experimental uncertainties involved in determining the critical speed, we estimate a value in the range 4-5 cm/s for a laser power of 1.5 kW.

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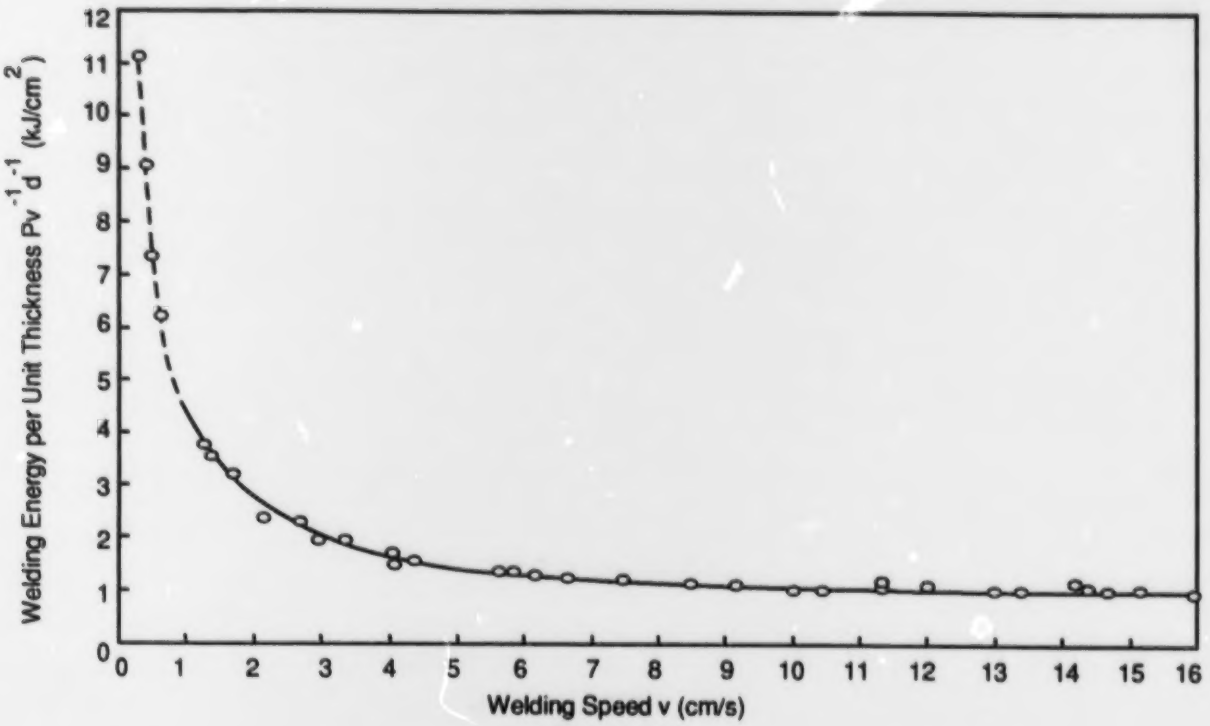

Figure 1

Experimental data on the variation of the welding energy per unit thickness as a function of welding speed for mild steel samples 0.64 to 2.6 mm thick. Laser beam polarization is parallel to the weld seam and the mode is TEMoo. Data above 1 cm/s are fitted to an analytical expression.

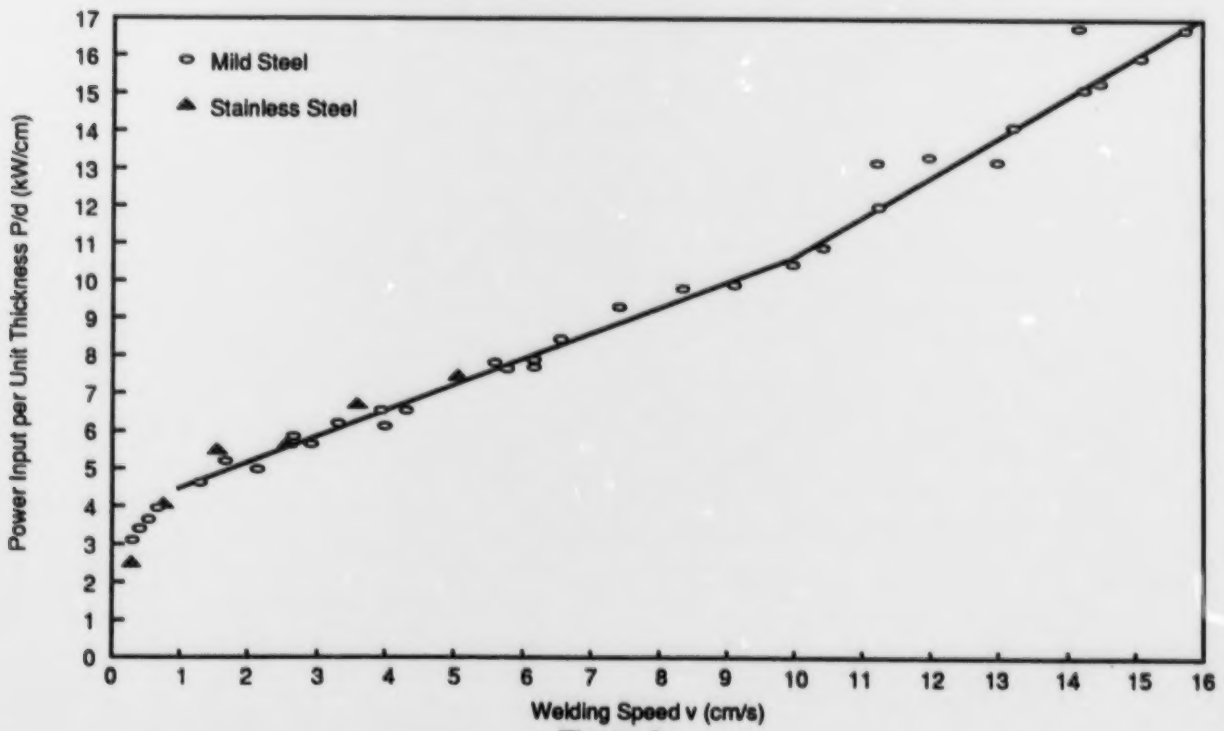

Figure 2

Experimental data on the power input per unit thickness as a function of welding speed for mild and stainless steel samples. The two lines represent linear fits to the mild steel data.

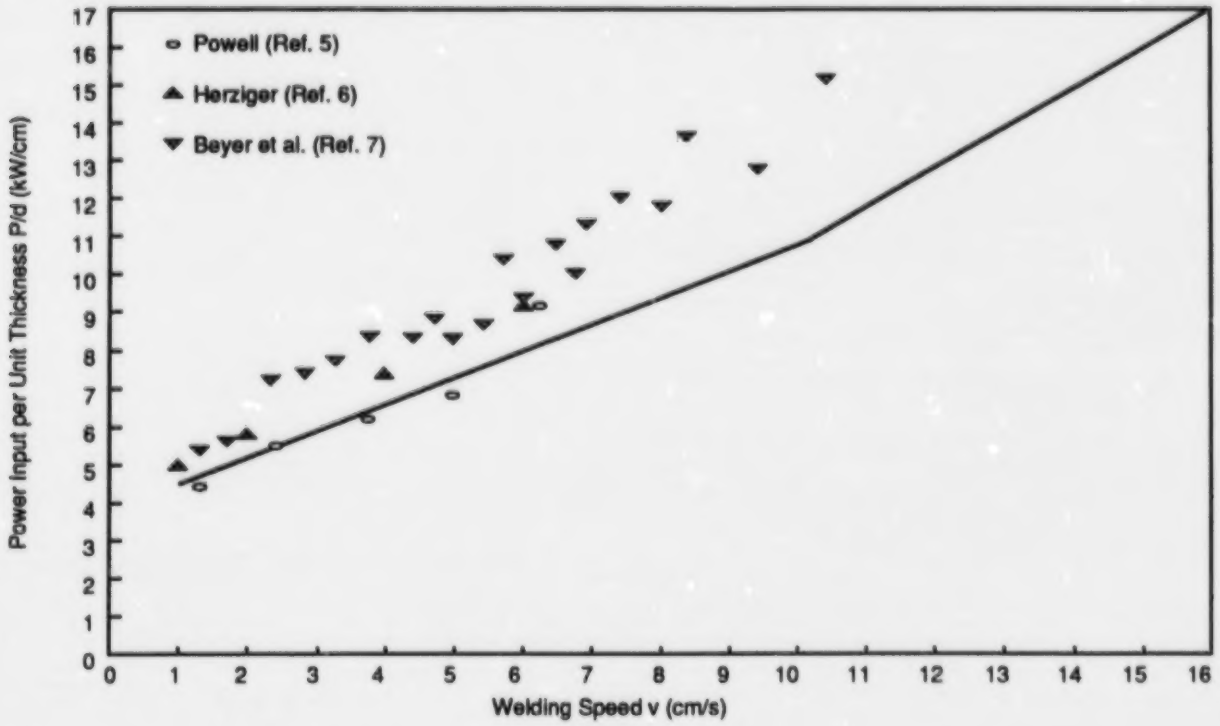

Figure 3

Experimental data from previous research showing the variation of power input per unit thickness with welding speed for mild steel. The lines represent fits to the present data (figure 2)

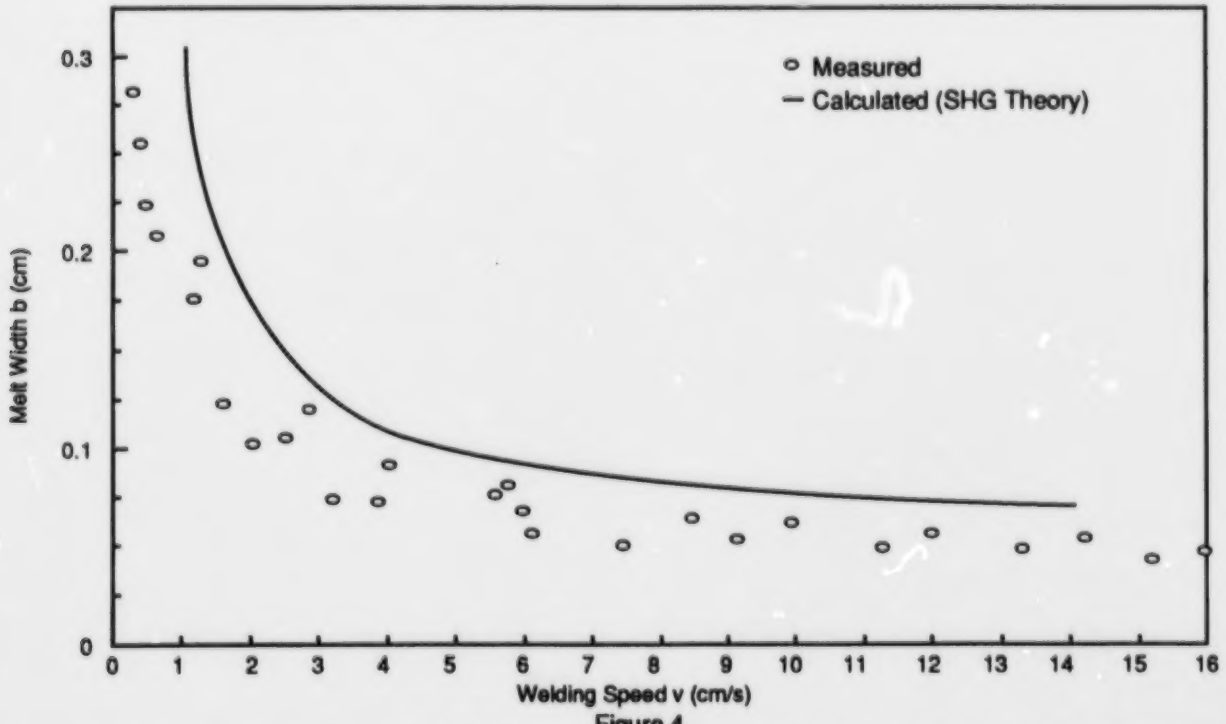

Figure 4

Measured melt width of laser welded mild steel samples as a function of welding speed (open circles). The solid line is derived by applying the Swift-Hook and Gick theory of laser welding to the experimental data of figure 1.

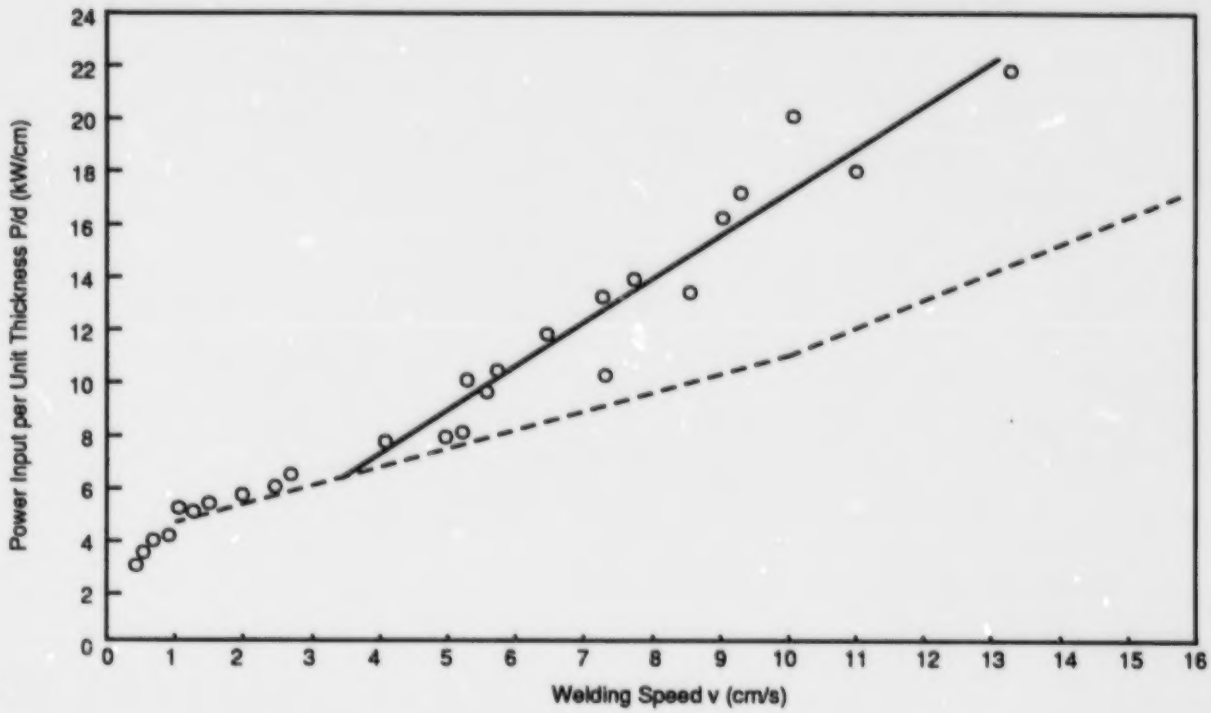

Figure 5

Experimental data for mild steel samples showing the dependence of power input per unit thickness on the welding speed for laser beam polarization perpendicular to the weld seam. The solid line is a linear fit (P/d=1.74v) to data above 3 cm/s and the dashed lines represent the results with parallel polarization.